

# Parallel Local Search: Experiments with a PGAS-based programming model

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**Abstract.** Local search is a successful approach for solving combinatorial optimization and constraint satisfaction problems. With the progressing move toward multi and many-core systems, GPUs and the quest for Exascale systems, parallelism has become mainstream as the number of cores continues to increase. New programming models are required and need to be better understood as well as data structures and algorithms. Such is the case for local search algorithms when run on hundreds or thousands of processing units. In this paper, we discuss some experiments we have been doing with Adaptive Search and present a new parallel version of it based on GPI, a recent API and programming model for the development of scalable parallel applications. Our experiments on different problems show interesting speedups and, more importantly, a deeper interpretation of the parallelization of Local Search methods.

**Keywords:** Parallel Local Search, GPI, Adaptive Search, Constraint Programming

## 1 Introduction

Systematic and complete search algorithms impose a limitation on the problem size they are able to solve due to the exponential increase in processing time and memory requirements. For this reason, heuristics-based search algorithms are used (and necessary) for larger problem sizes. Instead of exploring the complete search space, heuristics are used to guide the search to portions of the search space where solutions might be found. Local Search and Meta-heuristics are an interesting paradigm for combinatorial search and have been shown very effective for solving real-life problems [9,8]. But despite the effectiveness of local search methods, for really large problem instances, the running time required might still be substantial. One way to cope with this problem is by introducing parallelism.

The current trend we are facing is an inevitable paradigm shift towards multicore technologies where parallelism is now omnipresent. In recent systems parallelism spreads over several systems levels and heterogeneity is growing on the

node as well as on the chip level. Data must be maintained across a hierarchy of memory levels and most applications and algorithms are not yet ready to take full advantage of available capabilities. There is a demand for programming models with a flexible threads model and asynchronous communication to cope with this gap.

PGAS (Partitioned Global Address Space) programming models have been discussed as an alternative to MPI [12] for some time. The PGAS approach offers the developer an abstract shared address space which simplifies the programming task and at the same time facilitates data-locality, thread-based programming and asynchronous communication. GPI is a PGAS API that follows this philosophy and delivers the full performance of RDMA-enabled<sup>4</sup> networks directly to the application without interrupting the CPU.

In this paper we aim at bringing together both the need for parallelism to solve large problem instances with Local Search and its availability in current systems. We implemented a new parallel version of the Adaptive Search algorithm based on GPI that goes beyond the simple independent multiple-walk. Our new design shows interesting speedup gains on benchmarks with scalability problems and more importantly, a deeper interpretation on the parallelization of Adaptive Search in particular and Local Search methods in general, based on some characteristics of the benchmarks.

The rest of the paper is organized as follows: in section 2 we present GPI and its programming model, highlighting some its major features. Section 3 provides some background on the Adaptive Search algorithm and section 4 focuses on its parallelization. In section 5, we detail our parallelization strategy based on GPI and in section 6 we show the obtained results and compare it to the previous implementation. Section 7 examines and interprets our experimental findings, correlating them with the characteristics of the problems. Finally, section 8 presents a short conclusion and perspectives of future work.

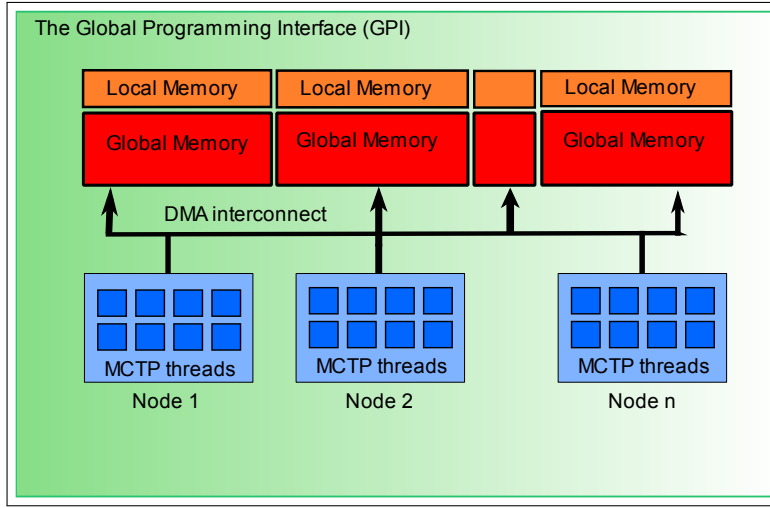
## 2 GPI

GPI (Global address space Programming Interface) is a PGAS API for parallel applications running on clusters. The thin communication layer delivers the full performance of RDMA-enabled networks directly to the application without interrupting the CPU. Fig. 1 depicts the architecture of GPI.

The local memory is the internal memory available only to the node and allocated through typical allocators (e.g. malloc). This memory cannot be accessed by other nodes. The global memory is the partitioned global shared memory available to other nodes and where data shared by all nodes should be placed. The DMA interconnect connects all nodes and is through this interconnect that GPI operations are issued. At the node level, the Manycore Threading Package (MCTP) is used to take advantage of all cores present on the system and make use of the GPI functionality and global memory. The MCTP was developed to

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<sup>4</sup> RDMA - Remote Direct Memory Access.



**Fig. 1.** GPI

help programmers take better advantage of new architectures and ease the development of multi-threaded applications. The MCTP is a threading package based on thread pools that abstracts the native threads of the platform.

GPI is constituted by a pair of components: the GPI daemon and the GPI library. The GPI daemon runs on all nodes of the cluster, waiting for requests to start applications and the library holds the functionality available for a program to use: read/write global data, passive communication, global atomic counters, collective operations. The two components are described in more detail in our previous contribution [10].<sup>5</sup>

The GPI core functionality can be summarized as follows:

- read and write global data
- passive communication
- send and receive messages
- commands
- global atomic counters and spinlocks
- barriers
- collective operations

In the context of this work, the most important functionality is the read/write of global data.

Two operations exist to read and write from global memory independent of whether it is a local or remote location. One important point is that those operations are one-sided that is, only the peer that issues such operation takes part in it. This is different from a two-sided scheme (message passing) where the

<sup>5</sup> GPI was previously known as Fraunhofer Virtual Machine (FVM).

peer that sends (*sender*) has a corresponding peer (*receiver*) that needs to issue a receive operation. Moreover, this functionality is non-blocking and completely off-loaded to the interconnect, allowing the program to continue its execution and hence take better advantage of CPU cycles. The data movement does not require any intermediate buffers and protocols to maintain those buffers. If the application needs to make sure the data was transferred (read or write), it needs to call a wait operation that blocks until the transfer is finished and asserting that the data is usable.

### 3 Adaptive Search

Local Search is based on the simple idea of “searching” by iteratively moving from one solution to one of its *neighbours*. The neighborhood of a solution is the set of solutions that can be obtained by applying a *move*. A *move* is a local change (hence the name Local Search).

The mechanism used to select a neighbour and thus the definition of what constitutes a neighbourhood is the main issue that differentiates between different local search methods. In general, it is problem dependent and is related to the definition of the *objective function*.

The Adaptive Search method [4] is one of many different local search methods and has proved to be very efficient in the types of problems where it was tested. It is a generic, domain-independent constraint-based local search method.

This meta-heuristic takes advantage of the structure of the problem in terms of constraints and variables and can guide the search more precisely than a single global cost function to optimize, such as for instance the number of violated constraints. The algorithm also uses an short-term adaptive memory in the spirit of Tabu Search in order to prevent stagnation in local minima and loops. This method is generic, can be applied to a large class of constraints (e.g. linear and non-linear arithmetic constraints, symbolic constraints, etc) and naturally copes with over-constrained problems.

The input of the method is a problem in CSP format, that is, a set of variables with their (finite) domains of possible values and a set of constraints over these variables. For each constraint, an “error function” needs to be defined; it will give, for each tuple of variable values, an indication of how much the constraint is violated. For instance, the error function associated with an arithmetic constraint  $|X - Y| < c$ , for a given constant  $c \geq 0$ , can be  $\max(0, |X - Y| - c)$ .

Adaptive Search relies on iterative repair, based on variable and constraint error information, seeking to reduce the error on the worst variable so far. The basic idea is to compute the error function for each constraint, then combine for each variable the errors of all constraints in which it appears, thereby projecting constraint errors onto the relevant variables. Finally, the variable with the highest error will be taken and its value will be modified. In this second step, the well known min-conflict heuristic is used to select the value in the variable domain which is the most promising, that is, the value for which the total error in the next configuration is minimal. In order to prevent being trapped in local minima, the

Adaptive Search method also includes a short-term memory mechanism to store variables to avoid (variables can be marked Tabu and “frozen” for a number of iterations). It also integrates reset transitions to escape stagnation around local minima. A (partial) reset consists in assigning fresh random values to some variables (also randomly chosen). A reset is guided by the number of variables being marked Tabu. As in any local search method, it is also possible to restart from scratch when the number of iterations reaches a given limit.

## 4 Parallel Adaptive Search

When parallelizing an algorithm one aims at identifying hotspots and sources of parallelism. As with most of meta-heuristics, in Adaptive Search these sources of parallelism are essentially: (1) the inner loop of the algorithm *i.e.*, computing and combining the errors of variables and selecting the variable with highest error and (2) the search space of the problem.

The problem with exploiting the inner loop of the algorithm is its granularity: it is too fine-grained. The overhead associated with synchronization and dispatching of tasks comes at a too high cost.

The other main source of parallelism is the search space (domain) of the problem itself. Theoretically, this domain could be decomposed in several disjunct partitions to be explored in parallel and without dependencies. However, in practice, several issues arise with this. Each partition is in general still too large for a sequential execution and more importantly, not the whole search space is equally valid and the exploration should avoid areas of it that lead to poor solutions. Moreover, it is hard and expensive to control and maintain the search conducted in the different partitions since a Local Search algorithm only has a local view of the search space. One example is the class of problems that have the best solutions clustered in a certain ‘zone’ of the search space. In this case, the algorithm should converge to that zone but in case of parallel execution avoid too much redundant work.

The Adaptive Search method has already been subject to some research on its parallel behaviour. Previous work on parallel implementations of the Adaptive Search algorithm have mostly focused on independent multiple-walks, requiring no communication neither shared memory between processing units.

In [5], the authors present a parallel implementation of the Adaptive Search algorithm for the Cell/BE, a heterogenous multicore architecture. The system includes 16 processors (the SPEs) where each one starts with a different random initial solution. The PPE acts as the master processor, waiting for the message of a found solution. For such number of processing units, the results were very promising, achieving for some problems linear speed-up.

Further work with Parallel Adaptive Search continued to follow the same approach with no communication between workers but more interestingly, concentrating on cluster systems with a larger number of cores.

In [2], the authors experiment and investigate the performance of a multiple independent-walk on a system with up to 256 cores. The parallelization was done

with MPI and involves the introduction of a “communication step” which tests if termination was detected (a solution was found) and terminates the execution properly.

The presented performance results are relatively modest in terms of parallel efficiency and still far away for the ideal speed-up which contrasts with the results obtained at a smaller scale (ie. up to 16 cores) in previous work. This points out the need for better alternative strategies in order to better exploit large-scale parallelism.

Since that the independent multiple-walk approach still leaves space for improvement in terms of parallel efficiency and scalability for some problems, new ways to take full advantage of parallel systems must be found.

In [1], the authors experiment with more complex strategies, where processes exchange messages resembling branch-and-bound methods where the bound is exchanged between all participants. In their work, two alternatives are attempted: exchanging the cost of the current solution of each process and the current cost plus the number of iterations needed to achieve that cost. Unfortunately, both approaches do not achieve better results than an independent multiple-walk.

## 5 Adaptive Search with GPI

Previous work with parallel Adaptive Search provides some groundwork to build upon and has showed that some benchmarks exhibit scalability problems when run on a large number of cores.

GPI seems, *à priori*, an interesting match to the problem of parallelization. Local search methods work with local information, trying to progress and converge to solutions in a global search space, requiring low global information. However, in a parallel setting, communication and cooperation are crucial and in this case, required to overcome the low parallel efficiency in some problems. The communication with GPI is based on one-sided primitives that might benefit the local view on a global search space, allowing threads to cooperate asynchronously. Moreover, communication is very efficient as GPI exploits the full performance of the interconnect. Hence, we continue to explore ways to further improve the parallelization of the Adaptive Search algorithm, exploiting GPI and its programming model, with the objective of getting some further benefits. But more importantly, to find mechanisms, concepts or limitations that are general.

In general, we can define the following objectives:

- further investigate and understand the behavior of parallel Adaptive Search on different problems.
- investigate the possibilities given by GPI and devise more complex mechanisms for the parallel execution of Adaptive Search, improving its performance
- identify the, possibly new, problems generated by the previous point.

The new parallel version of Adaptive Search based on GPI includes two variants which we name TDO (Termination Detection Only) and PoC (Propagation of Configuration).

The TDO variant implements the simple independent multiple-walk and serves mostly as our basis for comparison. First, with the existing MPI version, making sure that the implementation is correct and the performance is as expected. Second, to allow us to measure the improvement (if present) obtained with the more complex PoC variant. The PoC variant introduces more communication and sharing between working threads, by means of GPI primitives and threaded model.

The next sections present the two different variants in more detail.

### 5.1 Termination Detection Only

The variant with Termination Detection Only (TDO) is rather straightforward and implements the idea of an independent multiple-walk: all available cores execute the sequential version of the Adaptive Search algorithm.

We name this variant as Termination Detection Only since it subsumes itself to a termination detection problem *i.e.*, detecting the termination of a distributed computation. Termination Detection is itself a subject of much research and several algorithms have been and continue to be proposed ([6,11,13]).

In the case of the Parallel Adaptive Search method, we are interested in detecting termination as soon as one of the participating threads has found a solution, instead of waiting for all threads to finish as some of them can potentially require too many steps in order to find a solution (it is enough to be trapped in a 'zone' of the search space with no possible solutions).

The implementation of this variant is simple as it only involves the implementation of a mechanism of triggering and detecting termination.

The GPI implementation follows a similar line of the previous work with MPI. Whenever a thread finds a solution, it triggers termination by writing to its peers that it has found a solution. Thus, the time of the parallel execution is the time taken by this fastest thread.

Other threads must detect termination. This is only possible by introducing a communication step inside the internal loop of the Adaptive Search algorithm. This is required since there is no other way for a GPI instance to react on an remote event (*i.e.*, termination) other than with communication. In this communication step, a check for termination is done on a particular memory address that is written on termination emission as described above. The communication step introduces some overhead that needs to be minimized. Thus the communication step is only executed every  $k$  iterations.

### 5.2 Propagation of configuration

The experiments in previous work and with the TDO variant have found that the simple approach to parallelization, namely, the independent multiple-walk, proves itself insufficient in obtaining parallel efficiency on some problems specially when experimenting with a large number of cores. Moreover, exchanging some simple information such as the cost leads to no improvement.

Hence, we aim at communicating more and more meaningful information, introducing cooperation. By cooperation we mean mechanisms that allow threads to share information about their state and thus benefit from the collective search. Also, we want to exploit the potential and benefits of GPI and its programming model (one-sided communication, no wait for communication, global access to data, threaded model, etc.).

One of the most powerful aspects of Local Search is its simplicity. And due to this simplicity, it is hard to extract what could be considered as meaningful information to be shared and communicated. One logical candidate not yet tried is the whole current solution or configuration. Because the term *solution* is sometimes misleading, we refer to the current solution as a *configuration*. The final solution represents the solution when the algorithm stops.

The used implementation of the Adaptive Search method deals only with permutation problems and thus, a configuration is the permutation vector of the problems' variables.

Similarly to other approaches to the parallelization of local search methods which introduce cooperation, several important questions arise, namely:

1. Who does the communication?
2. When to do the communication?
3. How to do the communication?
4. What to communicate?

Answering most of these questions requires carrying out actual experiments since the best and correct answer it is not, in our opinion, foreseeable.

Our approach, which we call Propagation of Configuration (PoC), aims at answering these questions and give a better understanding of how cooperation can help with increasing the scalability of Local Search in general and the Adaptive Search method in particular.

### **Who does the communication?**

Answering the question of who does the communication involves deciding whether a single thread or all threads actually perform communication. Note that by communication we mean that, in a distributed setting, messages between nodes are exchanged. In a single node and given the GPI programming model, we can benefit from the threaded-model and shared memory. Notwithstanding the best option for this, it is clear that all threads must benefit from it.

There are potential advantages and disadvantages with both options. If all threads perform communication, any shared resources must be protected by a mutual exclusion mechanism, which might suffer from high contention. Moreover, when all threads perform communication a lot more pressure on the interconnect follows, increasing the parallel overhead and with possibly a lot of redundant communication happening (the same configuration being communicated several times). But, on the other hand, there will be a rapid progress towards the best promising neighborhood, intensifying the search. Of course, this can be positive



but can also become dangerous since most of threads might get trapped in a local minimum or poor quality neighborhood. A good trade-off between intensification and diversification must be achieved.

If a single master thread communicates, the effects are potentially the opposite: less intensification but also less contention, less pressure on the interconnect and less redundant work.

Preliminary tests made clear that the best option is the one with a single communicating thread since it reduces the parallel overhead. Plus, with GPI, all threads in a single node benefit immediately from the results obtained by the master thread without any exchange of messages.

### **When to do the communication?**

The first possible answer to this question is to follow the same strategy as with the Termination Detection Only variant: introduce a communication step and perform communication every  $k$  iteration. The value of  $k$  is fundamental on how well this option might perform. With a low value (*e.g.*,  $k = 10$ ), a strong intensification of the search is achieved but with the danger that threads might give up too soon on a promising neighborhood. With a high value of  $k$ , we avoid that danger but less intensification will be achieved since less information will be propagated.

The other option is to not interrupt the normal flow of the algorithm for communication, letting the search progress normally and independently until a local minimum is achieved. Only at this point the configuration is propagated and possibly used. One danger however is if threads don't hit local minima that often, the propagation of configuration won't progress and some threads might never see an up-to-date configuration, achieving less intensification. A solution to this problem is to still have communication every  $k$  iteration, where threads simply keep the communication progressing but only use the propagated information when they are in trouble *i.e.*, hit a local minimum. However, this option increases the overhead by adding the extra communication step in some iterations.

In principle the second option might seem more promising as no disturbance is caused when the algorithm is progressing positively. But the forementioned danger that the propagation of configurations won't progress can have the consequence that there won't be a benefit from the communication scheme when compared to the simple TDO variant. We performed some tests on a problem with low number of local minima (Magic Square) and in fact, this is what happens.

Based on this reasoning, our chosen option to when to communicate is to have a communication step. Moreover, we still need to detect termination thus a communication step must be present, even if with a much lower influence in terms of overhead. Our PoC variant combines termination detection and the propagation of configurations in a single step that happens every  $k$  iterations and we focus on finding an optimal value for  $k$ .

### How to do the communication?

With this question, we consider a single alternative. Since we aim at large scale executions, we need an efficient approach. Communication is done in a tree-based topology, in which each node only communicates with its parent and children (if any). Currently, a binary tree is used but this can be parametrized at initialization. At each communication step, the propagation of the configuration is done either up (to parent) or down (to the children) the tree. This only happens if a configuration was propagated from the children (in case of the up direction) or from the parent (down direction). The propagation of the communication behaves then like a wave, up and down the tree, with possibly different configurations being propagated at different points of the tree and contributing to some diversification.

Communication is performed by using GPI one-sided primitives. A thread posts a write operation and returns immediately to work. The configuration to be propagated will be directly written to the memory of the remote node asynchronously, without any acknowledgement of it and overlapped with the algorithm's computation. The remote node on the other hand, on its communication step, checks if a valid configuration was written to its memory, decides how to act on it and propagates its decision further.

We consider this single alternative since it gives us a good balance between intensification and diversification and because having a tree-based topology provides an efficient pattern to achieve communication scalability. The final objective is to have a communication step with low overhead and here GPI provides us with mechanisms to do so.

### What to communicate?

The Adaptive Search method (as many other Local Search methods) is very simple and includes very few elements that can be communicated.

The proposed option already mentioned before, is to communicate a full configuration. To this, we only add the cost of the configuration as it is the metric to evaluate the configuration. Plus, computing the cost everytime we communicate a configuration is a source of extra overhead specially if a problem has a large number of variables.

Still, the question remains of which configuration to communicate. In our design the best configuration *i.e.*, the configuration with better cost is communicated. At a communication step, a thread decides to propagate its own current configuration or the propagated configuration(s).

Communicating configurations can be of advantage because it includes implicitly more information about the state of the search since it, in a sense, provides a semi-exact positioning within the whole search space. As the best configurations are being propagated, other threads that are currently on poorer neighborhoods might benefit from moving to the best ones. With the stochastic behavior of Adaptive Search and enough diversification, the whole search procedure can be performed on the best neighborhoods and possibly, converge faster to good solutions.

## 6 Experimental results

In this section we present the obtained results using different problems.

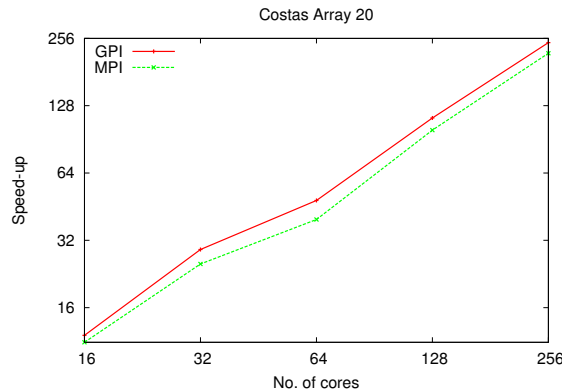
- **all-interval**: the All Interval Series problem (prob007 in CSPLib [7]),
- **costas-array**: the Costas Array problem,
- **magic-square**: the Magic Square problem (prob019 in CSPLib).

The experiments were conducted on a cluster system where each node includes a dual Intel Xeon 5148LV (“Woodcrest”) (*i.e.*, 4 CPUs per node) with 8 GB of RAM. The full system is composed of 620 cores connected with Infiniband (DDR). Since we aim at large scale, we performed our experiments on the system using up to 256 cores on some problems and 512 cores on others. This difference is due to the fact that the system is largely used and is hard to get access to the full system.

Note that Adaptive Search, as many other Local Search methods, has a stochastic behavior to achieve diversity on the search. To benchmark such behavior, several executions must be done and averaged. In our experiments we ran each problem 100 times in order to obtain meaningful results.

We compare both GPI variants (TDO and PoC) with the MPI implementation from previous work, which serves as our basis for comparison.

Fig. 2 depicts the obtained results for the Costas Array problem (CAP) with  $n=20$ .

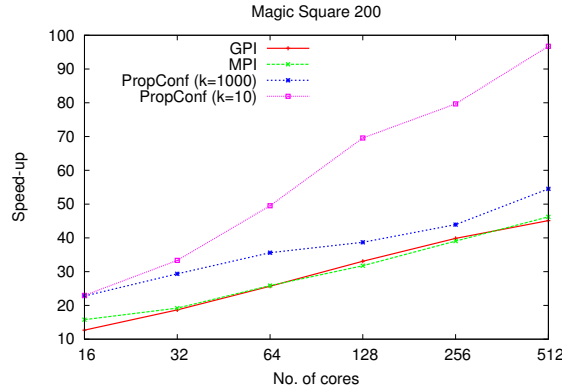


**Fig. 2.** Costas Array ( $n=20$ ) on 256 cores (64 nodes)

As already observed in previous work [3], the CAP shows an almost optimal scalability using an independent multiple-walk with no cooperation. We can observe that our implementation obtains similar, although slight better, results. This is the expected result since both approaches (TDO and MPI) are equivalent and a confirmation that our implementation performs as expected.

Although we aspired at obtaining even better results with the PoC variant (possibly super linear) for this problem, our experiments showed that this variant performs much worse than the simple TDO variant and thus we only present the speedup obtained with GPI using the TDO variant.

The Fig. 3 depicts the obtained results for the Magic Square problem up to 512 cores.



**Fig. 3.** Magic Square 200 on 512 cores (128 nodes)

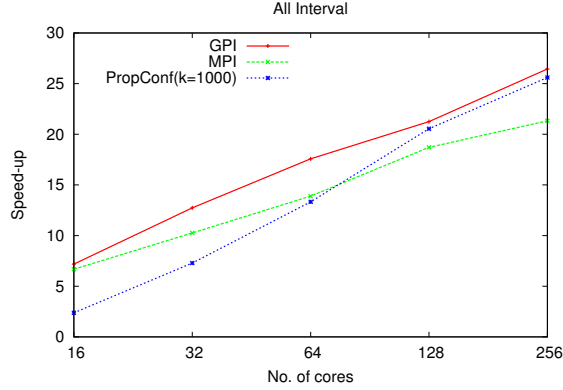
For this problem we present the speedup obtained with the TDO and PoC variants and compare it with the MPI version. The GPI TDO variant presents again, as expected, results similar to the MPI version.

The Magic Squares benchmark is one of the problems that results in disappointing scalability when using the simple independent multiple-walk and therefore a major target for improvement with more sophisticated approaches. Indeed, for this problem, our PoC variant improves the performance and scales better as we increase the number of cores used.

We wanted to answer the question of when to do communication: as we mentioned, in our preliminary experiments it turned out that the best approach is to have a communication step every  $k$  iterations where the value of  $k$  is decisive. Surprisingly, for this benchmark, a lower value of  $k$  ( $k=10$  in contrast to  $k=1000$ ) improves scalability by a factor of 2, achieving a speedup of 97 with 512 cores. Still a low parallel efficiency but a large improvement over the other options and variants.

The obtained results for the last problem, the All Interval series ( $n=400$ ), is shown in Fig. 4.

The All Interval Series benchmark is also one of the problems where good scalability was hard to reach when using a large number of cores. In Fig. 4 it is possible to observe this fact, where both the MPI and GPI TDO versions reach a modest speedup factor of 20 and 25, respectively (with 256 cores). Our PoC



**Fig. 4.** All Interval 400 on 256 cores (64 nodes)

variant however, performs much worse than the TDO variant at a low number of cores but it improves as we increase the number of cores, hinting that this variant can be of advantage if we increase the number of cores and the problem size. In Fig. 4 we only depict the obtained results for the PoC variant with  $k = 1000$  since, for this benchmark, it is the best value. In contrast to the Magic Squares benchmark, a lower value of  $k$  results in a much worse performance.

## 7 Discussion

The experimental results presented large differences in how the different problems benefit from parallelism and the implemented variants. One of our main objectives is to investigate and understand why this happens.

In order to be able to draw some conclusions on our experiments, it is important to characterize the chosen problems from different perspectives. We characterize the problems using different information such as the number of iterations and local minima. This characterization will give us a basis to better understand the problems at hand and possibly explain our results.

The Table 1 presents the obtained values for acquired information when running some instances of the previously presented problems. This information is the following:

**Problem** The problem instance.

**Iterations** The number of iterations required to find a solution.

**Local Minima** The number of local minima found.

**Resets** The number of partial resets performed (not full restart).

**Same var / Iteration** The number of times that existed more than one candidate variable (highest error value) to be selected.

Problem	Iterations	Local Minima	Resets	Same var/Iteration
Magic Square 200	413900.505	25864.75	3.01	23.36
Costas 18	389932.263	204024.89	204024.89	1.00
Costas 19	3364807.772	1714299.50	1714299.50	0.99
All Interval 200	11229.220	495.27	495.27	5.97
All Interval 400	41122.406	1422.15	1422.15	9.19

**Table 1.** Information collected for different problems instances.

This information allows us to better understand how does the Adaptive Search algorithm progress towards a solution, the neighborhood structure and extract further information (*e.g.*, number of local minima *per* iteration).

From Table 1 we can see that the different problems exhibit a quite different behavior. The Magic Square problem performs a low number of partial resets when compared to the total number of iterations or to the number of identified local minima. On the other hand, it is the problem where the number of candidate variables per iterations (Same var/Iteration) is high, meaning that at each iteration there are several possible moves towards the next configuration.

The Costas Array problem exhibits a completely different behavior. In this problem, the number of local minima identified is very large (almost every second iteration finds a local minimum) and the number of partial resets is very high, coincident with the number of local minima *i.e.*, at each local minimum found, a partial reset is performed. Also the number of possible moves at each iteration is close to 1.

The All Interval problem is yet another kind problem. Here, the number of resets is as with the CAP equal to the number of local minima but these happen much less often. The number of possible variable choices or moves is higher than 1, meaning that some diversification could be achieved.

If we relate this characterization of problems with the obtained experimental results, some conclusions can be conjectured in order to better understand the parallelization of such algorithm or, more concretely, how much can it benefit from a communication scheme such as the one we designed.

We argue that one critical aspect is the neighborhood of a configuration or the set of possible moves, which define transitions between configurations. Since we are propagating configurations we can look at our problems at hand according to this aspect. If a problem has a dense neighborhood or, in other words, the set of possible moves at each transition is (much) larger than one, each of these moves can be explored in parallel. Thus, when a promising configuration is propagated and several moves are possible and explored in parallel, the probability that one of these moves leads to a faster path towards an optimal solution increases.

Another important aspect is the number of local minima and resets and how both relate. A problem that finds a large number of local minima before encoun-

tering an optimal solution benefits less from processing a configuration which seems promising. This configuration is heuristically promising but in reality this information is less meaningful than it should. Similarly, a problem with a high number of partial resets suffers from the same problem.

Looking back at our experimental results with the different problems, we can better understand a) the difference in scalability and b) the improvement factor brought by the PoC variant to some problems.

In the Magic Square problem, each configuration has a dense neighborhood and benefits from the parallel exploration of different moves. Thus, the PoC variant improves the performance and scalability of the algorithm. When a working thread adopts a propagated configuration, it will define its own path from that configuration and differently from one other thread that receives that same promising configuration. Moreover, this problem has a low number of local minima and resets meaning that paths from one (initial) configuration towards an optimal solution are a series of transitions from neighbor configurations.

The Costas Array Problem exhibits optimal scalability with the independent multiple-walk MPI version or with our TDO variant and this is already *per se* satisfactory. On the other hand, it performs worse with the PoC variant: propagating a configuration is only a source of parallel overhead and will limit the search allowing less diversification. A propagated configuration will allow, on average, a single move and two threads taking the same configuration results in redundant work which is also probably unfruitful since the CAP is one of the problems with a high number of local minima and reset. This also explains the good scalability using the TDO variant, where increasing the number of cores allows covering more of the total search space together with the fact that solutions for this problem are well spread over it.

Finally, the All Interval Series problem shows a mixed behavior. Similarly to the CAP, the larger number of local minima found and same number of resets point to the same problem. There is less benefit from taking a propagated configuration since its meaningfulness is low. The PoC variant only introduces unnecessary overhead and this could explain the much worse performance at a lower number of cores. On the other hand, and similarly to the Magic Square benchmark, there is more than one possible move, on average *i.e.*, some diversification can be achieved. With a large enough number of cores, the parallel overhead can be amortized by the gain obtained with this diversification. This could be the reason for the steeper curve for the PoC variant on Fig. 4. Of course, with further experiments we will be able to understand this better.

In summary, problems where configurations have a denser neighborhood benefit from a cooperation scheme such as the PoC variant where the full configuration is communicated. Contrarily, problems that follow a trajectory with a single move possible won't benefit from a communication scheme that propagates the best current configuration. Also, if a large number of local minima is found and partial resets are required in the same number, the expectation for improvement in performance is zero.

## 8 Conclusion

In this paper we presented our work on the parallel implementation of the Adaptive Search method using a different programming model. GPI is an API designed for high-performance and scalable parallel applications. We aimed at investigating and understanding the behavior of Adaptive Search in a parallel setting, focusing on different problems particularly those that, in previous work, showed scalability problems when targeting a large number of cores. GPI and its programming model allowed us to design a new communication and parallelization scheme which in our experimental evaluation allowed a gain of a factor of 2 in terms of speedup for some problems. More importantly, it provided deeper insight and understanding on the parallelization of Local Search methods given different problems with disparate characteristics such as the neighborhood of a configuration, the number of local minima and partial resets.

In the future, we intend to examine our design and conclusions with other larger problems and experiment with complexer parallelization schemes. One possible direction is instead of using promising information (configurations, cost, statistics) directly, act on the complement of it, avoiding redundant work and cover as much as possible from the search space since this is the main source of parallelism.

One of our potential final goals is the design of a new Local Search algorithm more amenable to parallelization that builds upon these experiences.

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